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THE SUNDAL DRAINAGE SYSTEM IN CENTRAL NORWAY.

BY

R. L. BARRETT.

Introductory.—This paper originated in a study of Norway made in the geographical laboratory at Harvard College. From the laboratory I went into the field in the summer of 1897, and made a hasty examination of various points on the coast and on the highland of Norway, travelling by sea and land from Hardanger fjord in the south to Vardö in the north. The results obtained led me to concentrate my attention in the summer of 1898 on the region between the Romsdal and Trondhjem. Several rainy months flew by in the study of the valleys in this region, those of the Sundal system in particular. When the snow drove me from the field Dr. Hans Reusch, chief of the Norwegian Geological Survey, very kindly offered every facility for working up the results in Kristiania. Later on, before completing this paper, I had the advantage of talking the work over with Prof. W. M. Davis. Both Prof. Davis and Dr. Reusch have very kindly read and criticised the manuscript.

Valleys and Watersheds in Norway.—The two distinct sets of valleys which Prof. E. Richter* describes for southern Norway are well represented in the north. Everywhere comparatively shallow valleys may be seen mouthing high and abruptly on the walls of deep cañons. The southern high valleys, Richter says, are remnants of old and comparatively shallow valley systems which once headed near the present watershed of the country and drained west along the lines of the present deep fjords and fjord valleys. To-day's disjointed relation between the old high valleys and the young fjord valleys or cañons he explains by supposing that at various times during the glacial period the swifter and stronger ice-streams moved down the trunk valleys, while the slower and weaker streams followed the tributary valleys. As a result the trunk valleys wore down rapidly and began to break joint with the tributaries. At other times during this period, when the great glaciers retreated from the trunk valleys, névé continued to lie on the surface of the uplands and little glaciers gathered in the higher tributaries. Thus the trunk valley floor, exposed to the action of running water while all other parts of the system were protected by the ice cover, tended still further to break joint with the floors of the tributaries.

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* Geomorphologische Beobachtungen aus Norwegen, Sitzungsberichte der k. k. Akad., Wien. Math-naturw. Classe. Bd. 105, Abth. I, 1896, p. 147–189.

There are plenty of remnants of these old upland valley systems in the south between the Skager Rak and the Atlantic, heading on the main watershed of the country, and trending west. Similar remnants occur on the opposite side of the divide, trending southeast. These normal conditions—mature valleys heading on either side of the divide and draining away from it—appear to prevail as far north as the Ottadal (plate 1). Beyond this there is a striking change, which begins about 30 kilometres south of the mouth of the Romsdal, where the main watershed turns from a north and south line to one almost east and west. The watershed in the region of the Romsdal no longer lies between the heads of mature systems, one draining southeast and the other west; it lies instead on the floor of one of the southeast trunk valleys. The original heads of the southeast system lay many miles west of the present divide. These heads are now cut off from the southeast system, and drain as high valleys in a barbed or backhanded fashion into the deep young Romsdal cañon, whose stream flows northwest.

The New Boundary of the Sundal System.—North of the Romsdal system, and strongly resembling it, lies the Eikedal. Northeast of the Eikedal lies a variant from the Romsdal type, namely, the Sundal system, with which this paper is directly concerned. The gorges and cañons of the young Sundal system which drains northwest are divided from a certain mature valley system (hereafter called the Opdal system) which drains northeast and north, the streams from both systems reaching the Atlantic. The divide between them has suffered even a greater shift from west to east than was the case with the main divide in the Romsdal.

The object of the present paper is to present the arguments

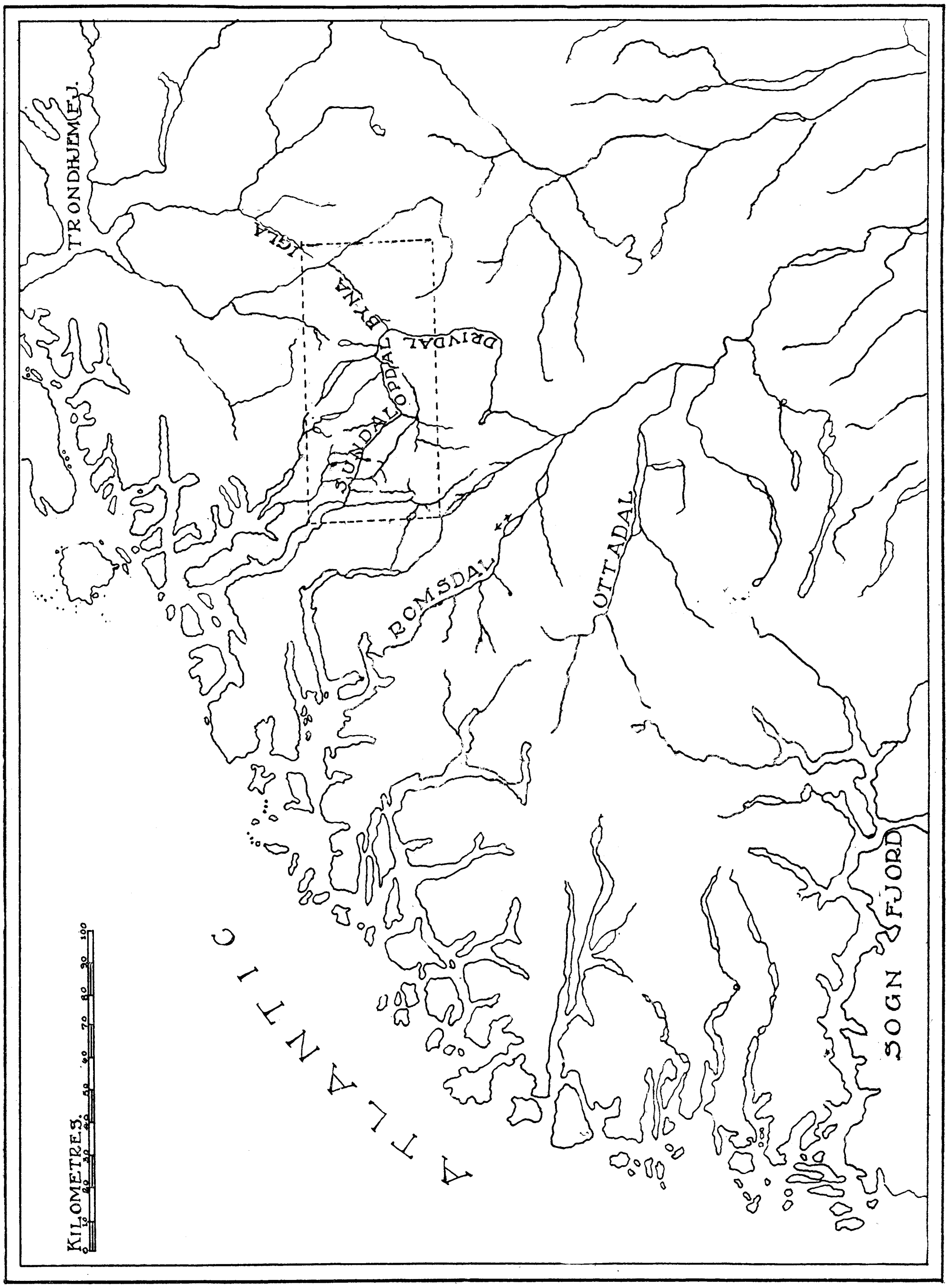

PLATE I.—OUTLINE DRAINAGE MAP OF CENTRAL NORWAY. THE RECTANGLE SHOWS THE AREA OF FIVE OUTLINE MAPS IN THE TEXT.

which have convinced me that the divide in question once stood near the head of the Sundal fjord, more than sixty-five kilometres west of its present position, which is just south of Aune in the mature trunk valley, and that the processes which shifted the divide are largely responsible for the peculiar features of the present Sundal system, with its cañons and high valleys.

My plan is: to reconstruct the mature valley system (Opdal) from its many disconnected ends; to describe the young cañon system (Sundal); to show the relations between the two; and to suggest explanations for these relations. Two sections headed "Details . . . ." contain accounts of certain items that are necessary to a full statement of the problem, but they may be passed over in a first reading.

Among the illustrations are five diagrams. On the first (Figure 1, plate 2), which is the name-key to the other four, there are several departures from the names given on the official map. For the sake of simplicity the names, North fork and South fork, have been applied to the branch cañons of the Sundal, and the name Gjeitdal has been extended to cover the lower as well as the upper part of a certain valley. The words, west and east, have been introduced at opposite ends of the Grödal for convenience in describing that valley. The suffix "dal" (valley), which appears in all the valley names on the key, has frequently been omitted in the text; the valley name being used alone.

The chief rocks, in the greater part of the region, which is shown in figures 1–5, are resistant archaean gneisses. Their folia have a fairly uniform strike across the region, about east and west, and a dip varying from perpendicular to nearly horizontal. The strike is crossed by the Sun and by some of the mature valleys diagonally. Others of the mature valleys are almost parallel to the strike, and still others cross it at right angles.

The Mature Opdal System.—The region is a highland, deeply dissected, but presenting comparatively even skylines. These become more and more even northeastward, as the surface falls off in height in that direction, until they form practically straight lines. Much of the highland surface is flat and quite as easy of access from the valleys as one valley is from another, but the highland does not attract farmers, for it is far too high to live on. In these latitudes there are few farms above 700 metres, and, as far as I know, none above 800; whereas the highland at its lowest is 1,300 metres and at its highest 1,800. It is almost absolutely barren; a high, cold

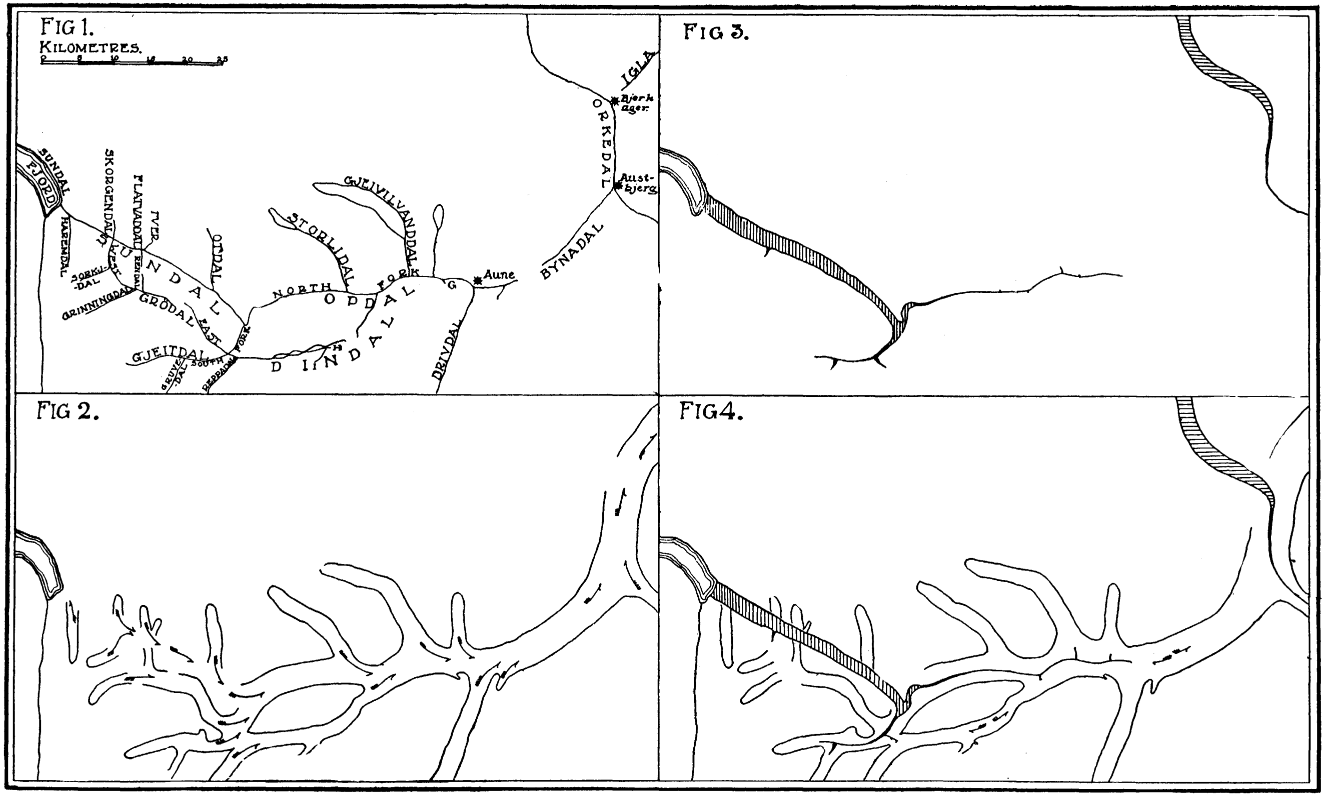

PLATE 2.—FIG. 1. LOCAL NAMES IN THE SUNDAL AND OPDAL SYSTEMS. FIG. 2. THE MATURE OPDAL SYSTEM. FIG. 3. THE YOUNG SUNDAL SYSTEM. FIG. 4. COMBINATION OF THE OPDAL AND THE SUNDAL SYSTEMS.

desert of rock and snow, relieved here and there by swampy or laked hollows. Although there is a vast quantity of fresh-looking rock waste over much of the surface, there is practically no fine soil. The cover of rock waste, attributed by Prof. A. Helland, of Kristiania, to frost work since glaciation, contrasts oddly enough with the bare rock in the floors of many of the high-level, mature valleys. In these, frost action seems to be much less active in splitting up the rock surface into coarse waste. The little fine soil which has formed has collected as black mud in the hollows, leaving much of the rock bare. The little mare which carried my pack, and was my only companion during a large part of the summer's work, could testify to all this; to the bleak highland, on the lower parts of which she spent more than one cold and hungry night, and to the equally bleak valleys where she found the edible grass blades—when there were any—growing a yard apart, and where she sometimes slipped and fell on the smooth, bare rock trails, and often had to struggle through the deep, sticky mud in the hollows.

The high-level valleys which are sunk beneath the highland in this region are of mature expression. In no sense are they valleys belonging to a peneplain, such as the highland may have been. If the highland country in which they lie has ever been a peneplain, it must have been greatly uplifted to enable the valleys to attain their present depths, and must have stood at the level then reached for a considerable time, to enable the valleys to attain their present low grades.

The high-level valleys of the region under consideration are not immediately connected to-day, but a study of their relations to one another shows that they once belonged to a large mature valley system which drained east and northeast from sources in the highland over the head of the present Sundal fjord to a station, Stören, some distance down the trunk valley of the mature system. Figure 2 (plate 2) shows this system from its western valley heads to within a few miles of Stören. The original plan of drainage and the relations of the various fragments to the system as a whole are shown by arrows. The accordance of the various valley floors throughout the system, despite the disconnected condition of the parts, is very striking. Practically all the heights along the floor of the trunk valley and along the floors of the connected and disconnected branches, except in one or two places where glacial obstructions occur, accord with the descending slope of a single valley system made up of all these pieces, as is shown by the altitudes on figure 5. Moreover, all the branches, except two short gulleys (H in the Din and G opposite the Gjeivilvand, figure 1), which appear to have been worn in fractures, trend in sympathy with, or at right angles to, the trunk of the system.

The lower part of the trunk valley is a broad, shallow, well-matured valley, incised in a particularly smooth part of the highland, which slopes gently down to the northeast. The upper part of the trunk valley and its branches are by no means as well matured as the lower. As a rule they are deeper and more steep-sided than the latter. Their steep-sidedness is appropriate in any case, as the lower course of a valley system always matures before the upper course. Their greater depths are due to the fact that while the grades throughout the system are fairly uniform, the highland in which the upper part is incised is very much more elevated than that in which the lower part is incised.

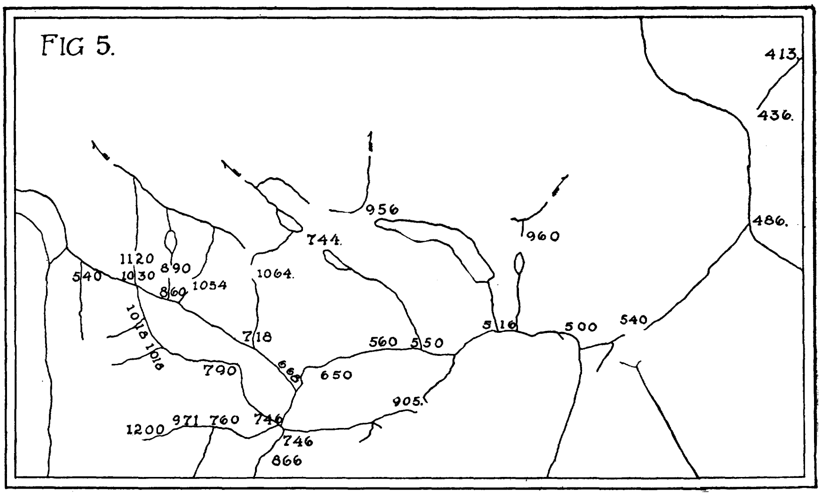

FIG. 5.—ALTITUDES, CHIEFLY IN THE OPDAL SYSTEM.

The rather gentle side-slopes of the shallow lower trunk valley were once heavily timbered, but are now more or less cleared of timber and used for hayfields. As the valley system ascends, its floor gradually rises above timber-line. Its uppermost parts, if bearing any trace of man at all, have nothing more than small rough stone huts, which afford a night's shelter to the passing hunter. A little lower down appear the saeter huts, where the women live in summer to milk the cows pasturing there and to make cheese and butter from the milk. Still lower down, the farms begin to appear; at first few and far between, then closer and closer together, until in the better-preserved middle part of the system a large portion of the broad valley floor is covered with farms and traversed by roads connecting them. All this stands in striking contrast to the entirely uninhabited highland surface in which this valley system is incised.

Being to-day composed of disconnected parts, this valley system, of course, has no one name, but instead a different name for every separate part, as may be seen by comparing figures 1 and 2. I shall call it for short the Opdal system, after the name of the most populous part of the trunk valley.

The Young Sundal System.—Turning now to the young cañons and gorges, represented alone in figure 3, plate 2, attention is first attracted by the great Sun cañon. The Sun extends, in southeastward continuation of the somewhat sinuous Sundal fjord, as a remarkably straight, broad and deep cañon for more than thirty kilometres through the highland. The cañon's floor near the fjord is eighteen hundred metres below the highland surface and more than one thousand metres below the floor of a certain high valley, a detached fragment of the mature Opdal system, which here mouths abruptly on the wall. The relief decreases somewhat up-stream as the highland surface falls off in that direction. Moreover, the highland south of the cañon, in this upper part, is lower than the highland north of it, because of a *graben*-like depression of the highland surface which lies between the Sun and the Grö.

The walls of the cañon are very steep, often inaccessible to within a hundred metres of the actual surface of the highland, where they flare out. The talus is scanty as a rule, and varies greatly in quantity from place to place. When present it is clothed with small trees and bushes on its lower slopes, but its upper slopes and the cliffs above it are bare. Here and there talus is altogether lacking, and the bare rock appears, smooth as if ice-rubbed. The cañon is floored with a flat drift plain, terraced by a stream which still runs on the gravels in a steep-sided trench. There is a quiet little village on the gravels at the cañon's mouth, and the broad plain back of the village is covered with farms and traversed by several roads. As the plain narrows up-stream, the farms become fewer and the several roads merge into the main highway.

Details of the Sundal System.—The average cross-section of the cañon is approximately that shown in figure 6. There is, however, a marked departure from this cross-section in the portion between the western Grö and the Harem. Here the southern side retreats, as shown by the dotted lines, and a strong cliff (A) extends parallel

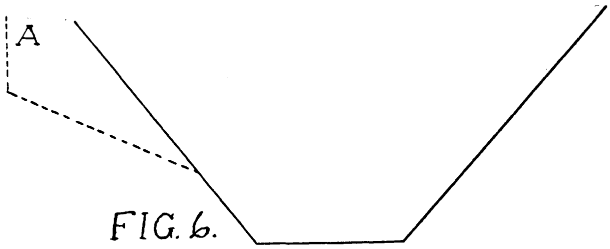

FIG. 6.—SECTION OF THE SUNDAL.

to the Sun from the Harem to the Grö. A weaker cliff but one on the same line as the other appears across the western Grö (B, figure 7). A short distance up the western Grö from the cliff, a fresh-looking crack, along which there appears to have been a slight vertical movement, crosses the valley on a line parallel with the cliff. The crack and the cliff, both thus approximately parallel to the Sun, taken in connection with the curious one-sided broadening of the Sun itself, between the Harem and the Grö, are suggestive of a small *graben* here.

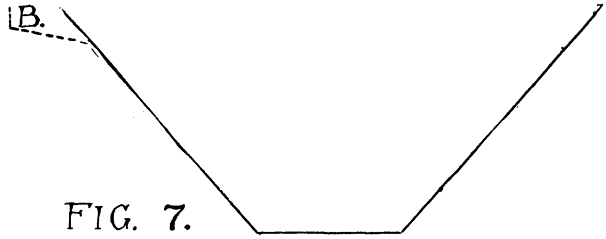

FIG. 7.—SECTION OF THE SUNDAL.

The deep and wide part of the cañon which I have been describing thus far heads abruptly against a low part of the highland; another *graben*-like depression. Branch cañons lead off at right angles to the north and south. These are much shallower than the main, because they are cut in the floor of the mature trunk valley of the Opdal system instead of directly in the highland. They are also much narrower. The one trending north, the North fork cañon, continues, drift-floored and habitable, for a few kilometres up-stream from the branching point. Then it swings round to the east and changes rather abruptly into a much smaller and generally narrow, uninhabitable stream-cut gorge, which extends on up to Aune in the mature trunk. As this narrow gorge is incised in a valley floor, which becomes lower and lower as it descends in the opposite direction to that in which the stream flows, the gorge shallows rather more rapidly than it otherwise would. Three very short branches lead off—one toward the Storli, one toward the Gjeivilvand, and one toward the Din. The South fork cañon, like the North, continues drift-floored and habitable for a kilometre or two up-stream, and then passes into another narrow, uninhabitable stream-cut gorge. The gorge swings round to the west and extends far up into the Gjeit, with a small branch in the Din and another in the Gruve.

A very striking feature of the Sun and the North fork, which together constitute the trunk cañon of the young Sundal system, is the habit of their tributary streams from the high mature valleys to trend, like barbs, out of sympathy with the trunk. This young trunk cañon, with its various branch cañons and the numerous high fragments of the ravaged old Opdal system, which now discordantly drain into it, constitute what I have called the Sundal system.

The Young Orke System.—There is another cañon, called the Orke, similar to the Sun, but shallower, which lies in the eastern part of the region. Like the Sun's forks, the Orke passes rather abruptly into a narrow, uninhabitable gorge, which extends from Austbjerg to Bjerkager and beyond (see figs. 1 and 3).

Relation of the Orkedal and Opdal Systems.—Thus far I have described the young Sundal and Orke systems and the mature Opdal system separately. Now, I propose to show their relations, as summarized in figure 4, plate 2. The lower trunk of the Opdal system appears, from most points of view, to be one continuous old valley. As a matter of fact, however, a stream from part of it escapes northward through the Orke cañon, which pierces the trunk valley side at Bjerkager; while a beheaded lower stream continues in the mature trunk valley, here called the Igla, toward Stören. The floor above Bjerkager, as before stated, is trenched by a narrow gorge, the continuation of the Orke cañon, as far as Austbjerg. The remnant lateral benches of the mature floor, each traversed by a road and occupied by farms, and the medial gorge, uninhabitable and impassable, between them, stand in striking contrast to each other. At Austbjerg the gorge switches off up a branch valley to the southeast, leaving the up-stream floor of the mature trunk valley intact, not trenched at all.

The stream in the trunk valley above Austbjerg is called the Byna; it is very small, and totally out of proportion to the valley. The size of the valley would lead one to expect, instead of a small, weak stream, a large river, well able to trench its valley floor. In fact, it can hardly be doubted that the Opdal trunk was once occupied by a large river flowing northeastward, whose upper waters have since been directed to some other discharge.

The Sundal and the Opdal Systems.—The diverted part of the Opdal drainage comprises, as may be seen by comparing figure 2 with figure 4, all the water south and west of Aune which to-day escapes westward in the gorges and cañons of the Sundal system. The diversion, as before stated, appears to have resulted from a shift of the Sundal-Opdal divide from its original position in the highland above the head of the Sundal fjord to its present position in the floor of the Opdal trunk near Aune. The divide lies to-day about six kilometres northeast of Aune on glacial material, which buries the rock floor at this point to a depth of thirty metres, or more.

A small branch valley just east of Aune trends in sympathy with the old system. Its stream, however, on entering the trunk, instead of finding a master flowing northeast, as it probably did before the above-mentioned changes, finds a very different state of things. It now joins, as a barb, a small stream heading on the modern divide of glacial material, and flowing backward into the head of the North fork gorge. The gorge leads the water west through the floor of the Op to the Sun. The large Driv also trends in sympathy with the Opdal system, and when seen from near Aune looks as if it must have been a branch of the trunk valley. Its stream, however, instead of flowing on down the trunk valley, as it doubtless once did, now bends sharply round, barb-fashion like the other, and flows with it into the North fork gorge.

The Op, in whose floor the upper part of the North fork gorge is cut, seems unquestionably to be a part of the trunk of the mature Opdal system. As has already been said, the floor of the mature trunk, formed by the Op and the various other valley sections, rises almost continuously from its lower part by Stören, to the southwest and west. There is but one exception to the general rise, namely, the divide formed just below Aune by glacial gravels, but these very probably overlie an uninterrupted rock slope. Four large tributary valleys enter the Op section at its floor-level. Three of these trend in sympathy with the trunk valley and one at right angles to it. Their streams fall, three of them barb-like, into the North fork, which leads their water west against the slope of the floor of the mature trunk valley.

The North fork gorge is very shallow near its head, hardly to be suspected in the broad Op floor. As it grows deeper and more cañon-like westward, it becomes broader and more conspicuous; while the mature floor which once stretched all across the valley dwindles away to comparatively narrow and somewhat dissected benches on either side.

The broad, mature floor of the trunk valley and its branches in the Op section are occupied by farms and by roads connecting them. Several farms stand abreast in the lower part of the Op. As, however, the uninhabitable gorge gains in size westward, the farms are forced into single file on the narrow remnant benches of the mature trunk valley. One good road on the north and a bad one on the south suffice to connect them. As the lower part of the North fork is approached the highway on the northern bench descends, cutting its way in the cliff on the side of the gorge. It reaches the bottom just where the drift-plain begins. Soon after the road descends from the northern bench, the farms disappear from both benches and saeters only remain.

The mature trunk now swings round to the south along the line of the lower North fork. The continuation of the northern bench in this quarter becomes indistinct for a time, but presently reappears clearly in the shape of a long, flat-topped spur in the angle between the North fork and the main Sun. The spur corresponds to a broad, continuous bench which lies along the eastern side of the North fork, across the head of the Sun and along the eastern side of the South fork; also to a bench on the western side of the South fork.

The spur apparently lies where the mature trunk was joined by a branch coming from the west, along the line of the Sun. There are suggestions of remnant benches of such a branch valley even along the Sun's sides, but these are very faint and not to be depended upon. Remnants still more striking than benches, however, remain to mark a mature branch that has been destroyed by the erosion of the Sun cañon. These are an ascending series of high valleys which mouth abruptly on the Sun's northern wall (figures 2, 4, 5). The first one mouths at seven hundred and eighteen metres, fifty metres higher than the top of the spur, the next at eight hundred and sixty metres, and the next at ten hundred and thirty metres. All three have low grades, head on low divides, and trend in sympathy with the supposed branch. The Ot and Flatvad have cross sections like that of a deep bowl. The Skorgen's cross section is like that of a shallow bowl. Both the Skorgen and the Flatvad are very much shorter than the Ot. A fourth valley, the Sorkj (not Skorgen), also appears to be a fragment of the mature branch. It is one of the short, broad, shallow-bowl type. It trends in sympathy with the supposed mature branch and mouths high (ten hundred and thirty metres) and abruptly on the western wall of the western Grö. The western Grö, as stated above, enters the Sun at the floor-level of the latter as a deep young V, the only low normal tributary to the cañon on its whole course of thirty kilometres. In brief, the suggestions are that when the Opdal system was intact it had a long branch on the line of the Sun (but at a higher level) with all these short tributaries. To-day the floor of the branch is gone, and instead one sees the deep, young Sun cañon and its off-shoot, the western Grö, with the short tributaries mouthing high and abruptly upon their sides.

The Sun cañon not only runs the whole length of the lost branch of the Opdal, but also penetrates the floor of the mature Opdal trunk at the point where the lost branch once joined it. To the north and northeast extends the North fork cañon, which has already been described. To the south and southwest one can see the remnant benches of the partly matured trunk valley, with the South fork cañon between them. This cañon narrows and shallows up stream until it finally dies out far up the Gjeit, where the partly matured valley remains intact.

Details of the Grö, Din and Gjeit Valleys.—The eastern Grö, a low-grade valley, with a shallow-bowl cross-section, mouths abruptly on the southern wall of the South fork just before this cañon turns up the Gjeit. The eastern Grö's stream heads on an almost imperceptible divide, flows for a few kilometres on the gently sloping floor, and tumbles in a waterfall into the gorge. The very similar Din mouths opposite at the head of a short branch gorge; and between the Din and the Gjeit mouths the somewhat deeper and narrower Reppa. All four valleys mouth thus like spokes in a hub—three on the gorge and one with the gorge in its floor, as close together as they can squeeze in. This disposition of valleys is abnormal. It is probably due to the inosculation of two parts of the mature Opdal system; an extended Gjeit, forming the upper trunk of the system, and a Reppa-Din branch (figure 2).

The Din, although it bears but one name, has a low divide on its floor, from which one stream flows east and another west. It is what Richter calls a "double valley." The divide lies on glacial gravels which fill the valley from end to end. They may have been poured in at a curious opening (I on the key) in the southern wall which affords connection with high collecting grounds for snow. The gravel deposits are eroded, but little if any in the central portion; but at the mouths of the streams they are trenched down to the rock floor, some sixty metres below their surface. Much of the deposit between the divide and the western mouth was apparently formerly pitted with deep hollows and the hollows were filled with lakes. Since then the lakes have lowered their outlets in their kame-like barriers, and nothing now remains but a set of very shallow, almost streaming, water bodies. There is every reason to suppose that no divide exists on the rock floor itself under all these gravels, but that there is instead a continuous slope from the present visible rock floor in the western end down to that in the eastern end of the valley. If this is assumed to be so, it is necessary only to replace in imagination the lost part of the dividing wall between the Reppa-Din and the extended Gjeit to show what an appropriate head for the Din the Reppa is. The rock floor in the Reppa's mouth is practically at the same level as that in the Din's western mouth, a trifle higher if anything, and the trend of the valley is just as it should be to fit the Din. The Reppa-Din thus reconstructed would make a branch to the mature Opdal system, trending in perfect sympathy with it. On the other hand, if it is supposed that there were no Reppa-Din, but that the greater part of the Din drained west as now, the Din would have joined the extended Gjeit part of the mature trunk valley as a barb, trending quite out of sympathy with the Opdal system. It would have then formed one of the four valleys which to-day mouth abnormally, close together—three on the gorge and one with the gorge in its floor.

The Din for some reason is occupied by saeters only. Its former head, the Reppa, contains but one even of these, probably because of its depth and narrowness. The lower Gjeit is deserted because the gorge occupies most of its floor. A graben-like broadening in the central part of the last-named valley is, however, occupied by farms, and there are saeters where the intact floor of the upper part begins. In the mouth of the eastern Grö there are several farms, and up the valley are numerous saeters. The various benches between the mouths of the four valleys support two or three isolated farms.

The name Grö, like the name Din, applies to a double valley, with streams draining either way. On the flat divide in this valley, unlike that in the Din, bare gneiss appears through the glacial gravels. Just east of the divide the valley makes a sharp angular turn from east to south (figure 2). East of the turn a cross-section is like that of a shallow bowl. West of it the valley is broader still, with a cliff on the south and a rather gentle slope most of the way on the north. The floor has little slope either way for several miles. Some distance west of the divide the valley begins abruptly to deepen. It passes into a very deep, narrow U and curves round north as if about to mouth abruptly on the Sun's southern wall, like the Ot on the northern wall, but much lower than that valley and at about the same level as the Harem. It does not reach the Sun's wall in this form, however, for a narrow cañon starts in its floor two or three kilometres back from its mouth. This cañon widens and deepens towards the Sun, and as it does so the benches of the U floor on either side dwindle and finally disappear. The valley, instead of mouthing on the Sun as a high U, enters, as already stated, as a low V about at the Sun's present level.

A valley called the Grinning, whose cross section is like that of a shallow bowl, mouths abruptly high up the side of the deep narrow U of this western Grö, just where the U begins to swing round from west to north. The deep U thus intervenes between the shallow Grinning and the shallow central part of the Grö. The Grinning trends so nearly in the same direction as the central part of the Grö that one standing on the Grö's divide and looking west gains the impression that the Grinning is a detached fragment of a former Grinning-Grö branch of the Opdal system.

High-level Tributaries of the Sun Cañon.—The tale of the double valleys does not end with the Grö and the Din. The Ot, the Tver, the Flatvad, the Ren, and the Skorgen are all double valleys. Perhaps the most notable of the five is the Flatvad. It is a remarkably straight, deep, north and south trench, with an almost imperceptible divide, not two kilometres from the Sun. It mouths abruptly at both ends on cañon walls. Exactly opposite this valley across the Sun mouths the Ren. The Ren is a small double valley between the Grö and the Sun, trending in about the same direction as the Flatvad. An example of a different type is the Skorgen. The ascent to this valley from the Sun is very steep, like that to the Flatvad. The valley floor is fairly flat for several kilometres. Beyond this the floor rises abruptly in a vast wall, perhaps 100 metres high, which, save for a breach near its eastern end, completely blocks the valley. The traveller passing through the breach or climbing to the top of the wall and looking north finds himself on the edge of a great amphitheatre, whose floor lies three hundred metres below him. The valley looks as if made by two cirques at different levels, which wasted backward towards each other until the dividing wall between was breached, or until some other process than the wasting breached it. As in the case of the Flatvad, so here, there is a corresponding valley across the Sun directly opposite, namely, the Grö. But the Grö, unlike the small, shallow Ren, is a large, deep valley.

Thus far I have traced the mature system up the Gjeit, up the Grö to the Grinning, and up the Sun to the Skorgen and Sorkj. In so doing I have considered all the important valleys in the western part of the region under discussion except one—the Harem.

The Harem is a tributary to the Sun close to the fjord. The valley mouths at right angles to the Sun five hundred and forty metres above the floor of the latter, that is, at about the level the deep U of the western Grö would have if it reached the Sun's wall. The Harem is the deepest of all the high valleys. Its floor is one hundred and seventy metres lower than that of the Ot, the lowest of the high fragments of the Opdal system, and five hundred metres lower than that of the highest, the Skorgen. It is about as long as the Ot, and has a similar cross section, a deep U, but its fall from head to mouth is twice as great. The descent is chiefly in two steps, one of them very strong. Between the steps the valley is of rather low grade. The top of the upper step is the very high flat floor of a valley draining in the other direction. The extraordinary depth of the Harem and the Grö, as compared with the various valleys of the Opdal system described above, is rather remarkable. Possibly they once belonged to this system, but have since been acted on by ice, or some other agency, much more violently than their sister tributaries. Possibly the Harem belonged to a contemporaneous system draining northwest along the line of the present Sundal fjord. Such a system as this latter must, of course, have been very much shallower than the present fjord. On the other hand, it must have been much more deeply incised at its head than the mature Opdal system, which drained in the opposite direction.

Summary concerning Reversal of Drainage.—What I have tried to establish thus far is as follows: There was a large mature (Opdal) valley system rising in the highland over what is now the head of the Sundal fjord and draining east and northeast towards Stören. There was another system contemporaneous with this but deeper in its upper tributaries, which rose close to the head of the first and drained northwest to the sea. The divide between the two has shifted to such an extent that the greater part of the large mature system which formerly drained east and northeast now drains west against its old slopes in deep, young gorges and cañons. As the gorges and cañons deepen downstream through the rising head valleys of the Opdal system, the main Sundal cañon comes to be one thousand metres deeper than the highest head valleys that it dissects. In the cañoning, large portions of the mature valley floors have completely disappeared; and narrow benches alone remain to mark them elsewhere. In some of the larger branches of the mature system, that over the Sun in particular, the entire floor has disappeared, and the tributaries are left as isolated fragments of the lost branch, hanging up high on cañon walls.

Explanation of Reversal of Drainage.—Now that the main facts regarding the reversal of the drainage have been set forth, with such explanation of curious details as seemed necessary, I have some suggestions to offer as to the explanation of the reversal. It is manifest that the chief change occurred in the highland on the line of the former Sundal-Opdal divide, and especially where the great Sun cañon has been eroded across the divide. Several factors occur to me as probably instrumental in this change, namely, guided headward erosion by the Sundal system and capturing of the Opdal branches; unguided headward erosion and capturing; erosion by the outlets of ice-dammed lakes which overflowed from the Opdal system to the early Sundal system; and glacial erosion.

The general form of the land suggests headward erosion and capturing on the part of the early Sundal system, for the slopes on the west are steeper than those on the east, and the distance to the sea is shorter. These conditions prevail only in the reversed drainage area of central Norway north of the Ottadal (plate 1). South of the Ottadal, where there has been no reversal of drainage, the slopes and distances to the sea east and west are much more nearly equal.

The region is full of suggestions of fault lines. Most important among these are the boundaries of two large *graben*-like blocks mentioned above as lying low in the highland. Along these boundaries four of the more important of the valleys discussed have been excavated. Two of the valleys are notable for their angularity, and the third, the Sun, for its straightness. Headward erosion, guided by some of these lines of weakness, or even unguided erosion through the massive rock, might seem a reasonable process of capture and reversal of drainage were it not for the following important feature, which argues against the occurrence of either of these processes on a large scale: None of the diverted high-level tributary streams have trenched their floors to any considerable extent, and the smaller of them have not trenched at all. This quite excludes capturing from the upper part of the Sundal system, where the larger tributaries occur; for no one would believe that the slow process of headward erosion had power to cut a long cañon like that of the North fork, while a large diverted tributary valley like the Storli, whose mouth has been passed on the way, remains practically untrenched. On the other hand, the capture of the smaller high-level tributaries of the Sun cañon by headward erosion, although unlikely, is not altogether excluded. These tributaries are very weak and have little power to trench. The short trenches that they did cut, if they cut any, may well have been obliterated in a subsequent widening of the Sun cañon by ice. It seems, however, impossible, even in this district, to say how much capturing by headward erosion took place. Headward erosion and capturing thus appear uncertain in their application.

The ice of the glacial period has wrought many and great changes in all the valleys before and after the completion of the reversal of drainage, for every one of the valleys bears the mark of ice erosion more or less deeply. The shapes of most have been changed from the V section to the typical U section. The floors of some have been furrowed as if by a gigantic plough; and one long deep valley which lies at right angles to the ice movement has come to exhibit enormous examples of *roches moutonnées.*

But the first cause of the drainage reversal seems to me to be the overflow of ice-dammed lakes. If it is assumed that the mature Opdal system was practically intact in its western branches when the ice-sheet appeared, it is probable that a series of events somewhat like those set forth in the following paragraphs took place :

Reversal by Overflow of Ice-dammed Lakes.—As the glacial period came on, a vast quantity of water in east-sloping valleys was dammed back by the ice and forced to flow out to the west over cols in the highland; the Sundal cañon not yet being begun. As the ice-sheet advanced on the lower Opdal system, outlets from the heads of high-level valleys were found to the northwest. The first of these were closed as the ice continued its advance, and others further west at higher levels were chosen by the water. The Ot, for example, formed an outlet after the mouth of the Storli was closed. The Ot—then, doubtless, a normal tributary to the Opdal system—is now a double valley. It mouths on the north at the floor-level of a valley draining northwest, and on the south high up the Sun's wall. The next outlet, after this was closed, was through a gap in the highland where the Flatvad and the Tver are now. Previously streams in this gap had doubtless flowed south and joined a master in the normal way. Both masters must then have been at the level of the streams in question. To-day four of these streams run in two parallel double valleys. One of them so closely resembles a single valley that the one name—Flatvad—covers the whole. Both valleys mouth high and abruptly at either end on cañon walls, and their streams go tumbling down long distances in cascades and waterfalls to find their masters. Directly opposite the Flatvad, across the Sun, mouths the double Ren. Further west on the Sun, in a similar relation to each other, mouth the Skorgen and the western Grö. The Skorgen is a double valley, although of a different type than the Flatvad, and the double Grö mouths exactly opposite. The Grö to-day, to be sure, mouths many metres below the Skorgen, but this deepening may well have taken place since a time when the two were near a common level. As an outlet from an ice-dammed lake formed in the Grinning-Grö to a similar lake in the mature branch over the Sun, the then eastern Grö must have been shallow.

The form of the Flatvad and the Ren and the relations among all four valleys recall in a general way the cross valleys in central New York, described by Gilbert, Quereau, and Fairchild. In the neighborhood of Syracuse there are a number of streams flowing north in deep valleys between the spurs of an upland that slopes to the north. Through the spurs run several channels, opening at either end above the floors of the north-draining valleys, and sloping gently from the valley on the west to that on the east. The floor of each channel is higher than the upland surface about the channel next north. The channels between any one pair of north-draining valleys are roughly in line with those between the next pair. It is supposed that these channels were formed during the retreat of the North American ice-sheet by the overflow of the water along its southern margin.

The Norwegian cross valleys, in so far as they are due to the overflow of lakes dammed back by ice, were probably cut during the advance rather than the retreat of the ice. For when the water rose high enough to flow out directly west, the cutting of the present Sun cañon started and the level of the water began to be permanently lowered; hence on the retreat of the ice the Sun cañon would retain the overflow.

Erosion by Overflowing Glaciers.—Ordinary stream erosion ceased when the glacial sheet overspread the whole region, but then the ice and the streams under it continued the work that the lake-overflows had begun. Ice-streams doubtless crept through every valley in the region, whatever the relation of the valley's direction to that of the general movement, uniting, dividing, and uniting again until they reached the sea. The overflowing ice planed out the gorges which had been cut across the cols in the high-level valleys by the overflowing water. It ground the valleys down until their cross sections assumed the form of a shallow bowl, or deep bowl, or deep "U," according to local controlling conditions. Among these conditions were: the depth to which streams had already eroded trenches in the cols, and the relation between the direction of a valley and the direction of the chief glacial movement. The former condition would not only determine the form of a valley when the ice came upon it but also the thickness and weight of the glacier starting through it. The latter condition would determine the velocity of the ice movement. Two of the high-level valleys in the region which lie nearly at right angles to the general ice movement still retain the breaches in their cols; not sharply-cut gorges, to be sure, but narrow, ice-rounded troughs, as if the ice had at least been over the col but not in sufficient force to obliterate the gorge. If this much is true, it seems reasonable to go a step further and suppose that the amount of the discordance between many of the high-level valleys and the Sun is largely dependent on the relation between the weight and the direction of movement of the glaciers in the high-level valleys and the weight and direction of movement of the glacier in the Sun. It certainly seems probable that the Sun's floor began to break joint with the floors of its tributaries in this glacial stage of its development. It doubtless continued to sink below them even after the ice-sheet spread down to the sea, covering the entire surface, highlands and valleys alike, for the probable effect of the ice-sheet was to emphasize inequalities in the surface rather than to obliterate them. The weight being least on the highest surfaces, the ice probably did least erosion there. Being greatest in the deepest troughs, it probably did more erosion there. A trough already deep and parallel to the ice movement, like the Sun (parallelism as well as depth being a condition most favorable to the ice action), probably suffered the most intense glacial erosion.

When the ice retreat set in, the deepened western outlet by the Sun cañon came into play again. All the water in the region—a large quantity—drained out through it and doubtless deepened it a great deal. The insignificant streams once existing on the lines of the old high-level outlets returned, but did little excavating. They came tumbling down the wall of the new-made cañon in waterfalls, and perhaps cut short branch cañons of their own; but if they did, these were entirely obliterated by a second great glacier which, during another ice advance, ran through the Sun.

The cutting of the western Grö by stream erosion went on in much the same way as that of the Sun, and continued until the present Grö, or rather the Grö as it would be without the cañon in its floor, resulted. Probably about this time, or at any rate before the post-glacial cañon in the North fork was cut, water work again ceased throughout the system and another set of glaciers crept down to the sea.

This time a giant Sun glacier, formed by the confluence of smaller glaciers descending from the Op, the Gjeit and the Reppa, appeared and swept down past the mouths of the Op, the Grö and the Harem, with their pigmy glaciers. It is probable that these three valleys had not thus far broken joint with the Sun. But now, with the advantage already gained by the stream erosion plus the increased power of the glacier itself, the Sun glacier was able far to outdo all the little glaciers. It probably planed down the cañon's floor much deeper below the floors of the tributaries than the water had cut it. It certainly widened the cañon and steepened its side and end walls in a remarkable manner. When the ice departed, both side and end tributary valleys were left hanging high up on the Sun walls. The tributary streams when released all strove to trench. That of the South fork cut a long gorge, that of the Grö a short one, and those of the others none. The lake, still dammed by ice in the North fork, overflowed and cut the gorge described as reaching nearly back to Aune. When the lake disappeared, the Driv, instead of flowing down its old valley, found its way out through the gorge, thus completing the reversal of the Opdal system.